NASA TECHNICAL MEMORANDUM

NASA TM X-3189

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(NASA-TM-X-3189) IRRADIATION AND MEASUREMENTS OF FLUORINATED ETHYLENE-PROPYLENE-A ON SILICON SOLAR CELLS IN VACUUM (NASA) 12 p HC $3.25 CSCL 10A

N75-15585

Unclas

H1/93 08629

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Stanley J. Marsik and Jacob D. Broder

Lewis Research Center

Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1975

1. Report No. NASA TM X-3189	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle IRRADIATION AND MEASUREMENTS OF FLUORINATED ETHYLENE-PROPYLENE-A ON SILICON SOLAR CELLS IN VACUUM		5. Report Date January 1975
		6. Performing Organization Code
7. Author(s) Stanley J. Marsik and Jacob D. Broder		8. Performing Organization Report No. E-8109
		10. Work Unit No. 506-23
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

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17. Key Words (Suggested by Author(s))		18. Distribution Statement	
Radiation damage to FEP-A in vacuum Silicon solar cell covers		Unclassified - unlimited STAR category 93 (rev.)	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 11	22. Price* $3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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by Stanley J. Marsik and Jacob D. Broder

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SUMMARY

Silicon monoxide (SiO) coated silicon solar cells covered with fluorinated ethylene-propylene-A (FEP-A) were irradiated by 1-MeV electrons in vacuum to a fluence of 2.5×10^{16} electrons per square centimeter (an absorbed dose for the FEP-A of 6.75×10^{8} rads). The effect of irradiation on the light transmittance of FEP-A was checked by measuring the short-circuit current of the cells while in vacuum after each dose increment, immediately after the irradiation, and again after a minimum elapsed time of 16 hours. The results indicated no apparent loss in transmission due to irradiation of FEP-A and no delamination from the SiO surface while the cells were in vacuum, but embrittlement of FEP-A occurred at the accumulated dose.

INTRODUCTION

Fluorinated ethylene-propylene-A (FEP-A) has been proposed as a solar cell cover for use in outer space (ref. 1). The radiation damage properties of FEP-A must be determined before it can be considered for use as a solar cell cover material in a radiation environment. One of the important properties to be evaluated is its light transmittance after radiation exposure. In general, organic materials tend to darken upon exposure to heavy doses of ionizing radiation. It is, therefore, important to determine whether FEP-A film darkens when it is exposed to radiation. For the experiment described in this report, a thickness of 0.0127 centimeter was chosen because it is the closest commercially available thickness to the standard 0.015-centimeter (6-mil) cover glass. In previous investigations of this material the results were either obtained from testing in air after irradiation in vacuum (refs. 1 and 2) or not directly related to light transmittance (refs. 3 and 4). Most of the investigators concur that the absence of oxygen during the irradiation and the evaluation of the effects of irradiation in air are

responsible for marked changes of the physical, electrical, and optical properties of FEP-A. To preclude any unknown effects that may occur if the simulated exposure is done in one environment and the measurements are made in another, the measurements should be performed in the same environment as the exposure. This report presents in-vacuum measurements of the effects of 1-million-electron-volt (1-MeV) electron irradiation on FEP-A light transmittance and observations of the physical integrity of FEP-A after irradiation. Solar cells were used as a convenient device for these measurements.

The effects were measured by comparing the radiation-induced loss in short-circuit current of the FEP-A covered cells with the corresponding loss experienced by an uncovered cell of the same type. During each measurement, the FEP-A was observed for possible loss in adherence to the cell surface. After the final irradiation the FEP-A was also tested for embrittlement and delamination in an argon atmosphere before exposure to air.

EXPERIMENTAL APPARATUS AND PROCEDURE

A vacuum-tight chamber was especially equipped with necessary ports for electron-beam irradiation and solar simulator measurements and with electrical and thermocouple feedthroughs (fig. 1). This apparatus facilitates investigation of FEP-A film under vacuum. The specimen holder inside the chamber can be rotated from the outside to allow for inspection of the samples and to permit normal incidence of the light under the solar simulator after each irradiation. The chamber can be sealed while under high vacuum, decoupled from the beam transport pipe of the electron accelerator, and transported to the solar simulator facility for measurements of various parameters.

The vacuum leak rate of this apparatus is approximately 2×10^{-5} torr per minute. This allows almost 1 hour for handling in transport after decoupling from the vacuum system before the pressure within the chamber rises above the 10^{-4} torr range. In this experiment the time in transport was less than 15 minutes, and the chamber was immediately connected to another vacuum system. The pressure inside the vessel during the irradiation was 1×10^{-6} torr. Thus, during this experiment the samples were not subjected to a pressure higher than 3×10^{-4} torr until after the final irradiation and measurements.

The 15-centimeter-diameter quartz view port was protected from radiation damage by a 0.3-centimeter-thick aluminum shield fitted on the inside along the contour of the vessel and clamped to the rotating shaft. The specimen holder and the shield were rotated together for electron irradiation and for light-beam alinement.

The 1-MeV electron beam was provided by the Dynamitron potential-drop accelerator. The beam was focused to a vertical line of good uniform density and then moved to

scan a 4- by 10-centimeter rectangular area uniformly. This allowed simultaneous irradiation of four 2- by 2-centimeter solar cells. The dose received by the cells was measured directly by a Faraday cup behind a 0.3-centimeter-diameter entrance aperture. The charge intercepted by the Faraday cup was measured by a current indicator and integrator. The rectangular area of the scanned beam was continuously monitored at its four corners by four independent probes.

Solar cell electric output measurements were made by using individually insulated contacts, which also served to hold the cells in place. No attempt was made to control the temperature of the specimen holder; however, this temperature and the temperature of the cells were monitored with thermocouples. The specimen holder arrangement is shown in figure 2.

For each set of electrical measurements the light-beam intensity was set for air-mass-zero conditions at the test plane by monitoring the short-circuit current of two reference cells positioned on the specimen holder outside the electron-beam target area. The reference current value for these cells was established before the experimental measurements by using Lewis filter wheel solar simulator currents (ref. 5). The reference cells were rechecked after the experiment to ensure that air-mass-zero conditions were maintained.

Prior to the experiment the following 10 ohm-centimeter, 0.0305-centimeter-(12-mil-) thick silicon solar cells with silicon monoxide (SiO) antireflection coating were selected at random: three 2- by 2-centimeter FEP-A covered cells prepared by a silane (Union Carbide A 1100) treatment method (unpublished work of J. D. Broder at the Lewis Research Center), one uncovered 2- by 2-centimeter cell to be used as a control cell for investigation of the FEP-A covers, and two 1- by 2-centimeter quartz glass-covered cells to be used as the reference cells. The initial measurements of short-circuit current (I_{sc}) for the 2- by 2-centimeter test cells were made under the filter wheel solar simulator. All these cells were also checked for their open-circuit voltage (V_{oc}). Upon installation inside the chamber the cells were again measured for I_{sc} under a Spectrolab X-25 solar simulator with the intensity adjusted to match the previously obtained I_{sc} for one of the 1- by 2-centimeter cells.

To ensure that no pressure effect of short-circuit current existed, I_{sc} was measured at a pressure of 1 atmosphere and then again at a pressure of less than 1×10^{-4} torr. The readings were within ±2 percent of the I_{sc} previously obtained under the filter wheel solar simulator.

After the initial evacuation of the vessel the cells remained in vacuum throughout the test. The electron irradiation was stopped at accumulated fluences of 5×10^{14}, 1×10^{15}, 5×10^{15}, 6.5×10^{15}, 8×10^{15}, 1×10^{16}, 1.5×10^{16}, and 2.5×10^{16} electrons per square centimeter. Each time the cells were visually inspected through the window for physical damage and an average I_{sc} was determined from three readings under the

Spectrolab X-25 solar simulator. The I_{sc} of the irradiated cells was measured within 15 minutes after the irradiation was stopped and then again after a minimum elapsed time of 16 hours to determine any annealing effect. After the accumulated fluence of 2.5×10^{16} electrons per square centimeter the vessel was prepared for opening in such a manner that the samples would not be exposed to air before probing to test the physical integrity of the FEP-A. The top cover of the vessel was sealed in a "dry bag," which was purged and then backfilled with argon gas. The pressure inside the vessel was slowly increased by allowing argon gas to leak in until a slight positive pressure was obtained. The FEP-A was then probed for brittleness and adherence to the cell in the dry bag filled with argon gas. Only after this test were the cells exposed to air and were V_{oc} and I_{sc} remeasured.

RESULTS AND DISCUSSION

Measurements of V_{oc} of the three FEP-A covered cells and the uncovered control cell are shown in table I. The V_{oc} results before and after irradiation indicate that the samples were fairly uniform in characteristics and had resistivities very close to 10 ohm-centimeters.

Measurements and Observations in Vacuum

The I_{sc} measurements of the four cells taken initially and at various 1-MeV electron irradiation levels were averaged and are shown in table II. Each value listed is an average of three measurements. The temperature of the back of the cells during the irradiation stabilized at about 28° C for shorter dose increments and at about 30° C for longer irradiations.

The accumulated electron fluence of the FEP-A cover is more meaningful when expressed in terms of absorbed dose, in rads, where 1 rad = 100×10^{-7} joule per gram (100 ergs/g). This dose may be obtained to a reasonably accurate degree from the stopping power of silicon ((1.554 MeV)(cm^2)/g for 1-MeV electrons), determined by M. J. Berger and S. M. Seltzer (ref. 6), and by correcting the dose for the density of FEP-A (2.15 g/cm^3). Thus, for normal incidence of 1-MeV electrons, the absorbed dose in the FEP-A cover is 2.7×10^{-8} rad-square centimeter. The accumulated fluence of 2.5×10^{16} electrons per square centimeter represents an absorbed dose of 6.75×10^{8} rads.

An absorbed dose can be converted to an equivalent time in space by using reference 7. This reference presents tabulated information on equivalent 1-MeV electron fluence and absorbed dose due to the energy spectrum of trapped electrons in a synchro-

nous equatorial orbit. The effect of protons is negligible in this orbit. From table 6.8 of reference 7 the average absorbed dose at a depth of 0.0275 gram per square centimeter (0.0127-cm-thick FEP-A) is approximately 2.2×10^{7} rads per year for infinite backshielding. Since the cells used in this experiment would be backshielded in space with a combined thickness of FEP-A and Kapton of only 0.0183 gram per square centimeter, the front FEP-A cover would also receive a considerable dose through the back because of the omnidirectional nature of space radiation. This additional effect can be reasonably estimated from table 6.21 of reference 7, which gives the absorbed dose in silicon under a shield in a synchronous, zero-inclination orbit. With a shield of FEP-A, Kapton, silver contact, and silicon having a combined thickness of 0.1306 gram per square centimeter, the absorbed dose under this shield is approximately 2×10^{6} rads per year. Then the total dose in the FEP-A cover in synchronous orbit is about 2.4×10^{7} rads per year. Thus, the absorbed dose in this experiment, corresponding to an accumulated 1-MeV electron fluence of 2.5×10^{16} electrons per square centimeter, would be equivalent to the dose absorbed in about 28 years in orbit.

For comparison purposes figure 3 shows data from this investigation superimposed on the normalized I_{sc} data from reference 7 for uncovered 7- to 13-ohm-centimeter N/P cells 0.0305 centimeter thick illuminated at 135 milliwatts per square centimeter. The spread of the experimental data points may be attributed mainly to measurement reproducibility errors. The uncertainty of the accumulated fluence, based on previous experience, is a maximum of 10 percent.

No I_{sc} changes were observed between measurements taken immediately after irradiation and those taken after a minimum time lapse of 16 hours. This agreement indicates no annealing in vacuum of either the FEP-A cover or the cells.

The FEP-A cover does not change its transparency, as indicated by total I_{sc} measured under the solar simulator, even at an accumulated 1-MeV electron fluence of 2.5×10^{16} electrons per square centimeter (6.75×10^{8} rads of absorbed dose).

A photograph of the cells inside the vessel was obtained after the final irradiation increment, while they were still in vacuum, and it is shown in figure 2. No delamination of FEP-A or any other visible damage occurred to the cells. The cells were fully supported and subjected to no extraneous stresses, and they remained in this state until probed with a sharp object in an argon atmosphere. Probing revealed that the FEP-A film was brittle after the 1-MeV electron fluence of 2.5×10^{16} electrons per square centimeter. Attempts to lift and peel the FEP-A from the surface resulted only in removal of the cover immediately under the probe.

Measurements and Observations in Air

Upon removal of the cells from the argon atmosphere, I_{sc} and V_{oc} measurements were again made. The readings were in very close agreement with those obtained while the cells were still in vacuum. These measurements were repeated again after several hours. No changes were observed, which indicated that no annealing had taken place in several hours. Measurements made on the quartz glass window showed that no discoloration of the glass occurred during irradiation.

After 2 days of exposure to air, the FEP-A cover on cell 2 developed cracks and lifted from the silicon. When a portion of the cover was removed from the cell, it carried with it the antireflection coating. Therefore, the delamination occurred at the SiO-silicon interface and not at the FEP-A-SiO interface. Since this happened to only one of the three covered cells, no attempt is made to draw any conclusions from it. Figure 4 shows the condition of all four cells after 14 days in air. After this time period, short-circuit current of the two intact FEP-A covered cells showed no change from that taken immediately after exposure to air.

SUMMARY OF RESULTS

The following results were obtained from an investigation in which silicon solar cells covered with fluorinated ethylene-propylene-A (FEP-A) were irradiated in vacuum by 1-MeV electrons to a fluence of 2.5×10^{16} electrons per square centimeter (absorbed dose in the FEP-A cover of approximately 6.75×10^{8} rads): The cells showed no delamination and no more loss in short-circuit current than that experienced by an uncovered cell. There was no darkening of the FEP-A, which would have reduced the short-circuit current more than the reduction caused by the irradiation of an uncovered cell. The absorbed dose in the FEP-A cover was equivalent to the dose absorbed in about 28 years in a synchronous equatorial orbit.

Upon removal from vacuum, no increases in short-circuit current were noted, which indicated no annealing. At a 1-MeV electron fluence of 2.5×10^{16} electrons per square centimeter the FEP-A was very brittle. The fluence at which the brittleness began was not determined.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 3, 1974,
506-23.

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TABLE I. - OPEN-CIRCUIT VOLTAGE OF FOUR SOLAR CELLS BEFORE AND AFTER IRRADIATION

Cell	Cover	Open-circuit voltage before irradiation, $V_{oc,0}$, V	Open-circuit voltage after irradiation, $V_{oc,1}$, V	Ratio of open-circuit voltage, $V_{oc,1}/V_{oc,0}$
1	FEP-A	0.55	0.47	0.85
2	FEP-A	.54	.46	.85
3	None	.54	.46	.85
4	FEP-A	.54	.47	.87

TABLE II. - SHORT-CIRCUIT CURRENT OF SOLAR CELLS BEFORE AND AFTER IRRADIATION

[Short-circuit current before irradiation, $I_{sc,0}$; short-circuit current after irradiation increment, $I_{sc,n}$.]

Cell	Cover	1-MeV electron fluence, electrons/cm^2																	
		0		5×10^{-4}		1×10^{15}		5×10^{15}		6.5×10^{-5}		8×10^{15}		1×10^{16}		1.5×10^{16}		2.5×10^{16}	
		Short-circuit current																	
		I_{sc}, mA	$I_{sc,n}/I_{sc,0}$	I_{sc}, mA	$I_{sc,n}/I_{sc,0}$	I_{sc}, mA	$I_{sc,n}/I_{sc,0}$	I_{sc}, mA	$I_{sc,n}/I_{sc,0}$	I_{sc}, mA	$I_{sc,n}/I_{sc,0}$	I_{sc}, mA	$I_{sc,n}/I_{sc,0}$	I_{sc}, mA	$I_{sc,n}/I_{sc,0}$	I_{sc}, mA	$I_{sc,n}/I_{sc,0}$	I_{sc}, mA	$I_{sc,n}/I_{sc,0}$
1	FEP-A	134	1.0	116	0.866	113	0.844	103	0.769	103	0.769	99	0.739	100	0.746	96.3	0.719	93.2	0.695
2	FEP-A	132	1.0	115	.871	112	.849	102	.773	101	.765	97	.735	97.7	.740	93.9	.711	90.4	.685
3	None	137	1.0	122	.890	117	.854	108	.789	107	.781	103	.751	104	.759	100	.730	95	.694
4	FEP-A	133	1.0	119	.895	114	.857	105	.790	104	.782	101	.760	102	.767	98.2	.739	92.8	.698

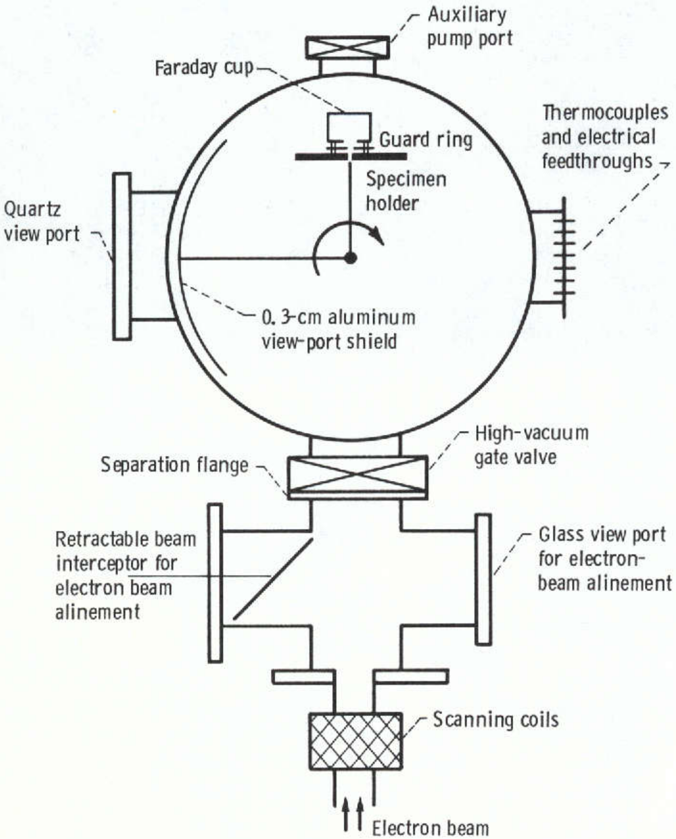

Figure 1. - Top view of experimental apparatus for irradiation.

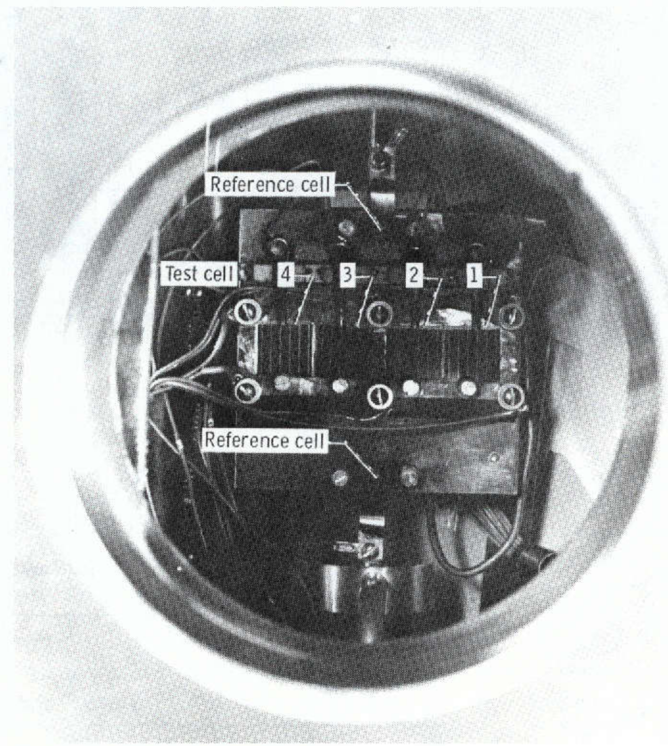

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Figure 2. - Cells in vacuum after last irradiation. Test cells, 2 by 2 centimeters; reference cells, 1 by 2 centimeters.

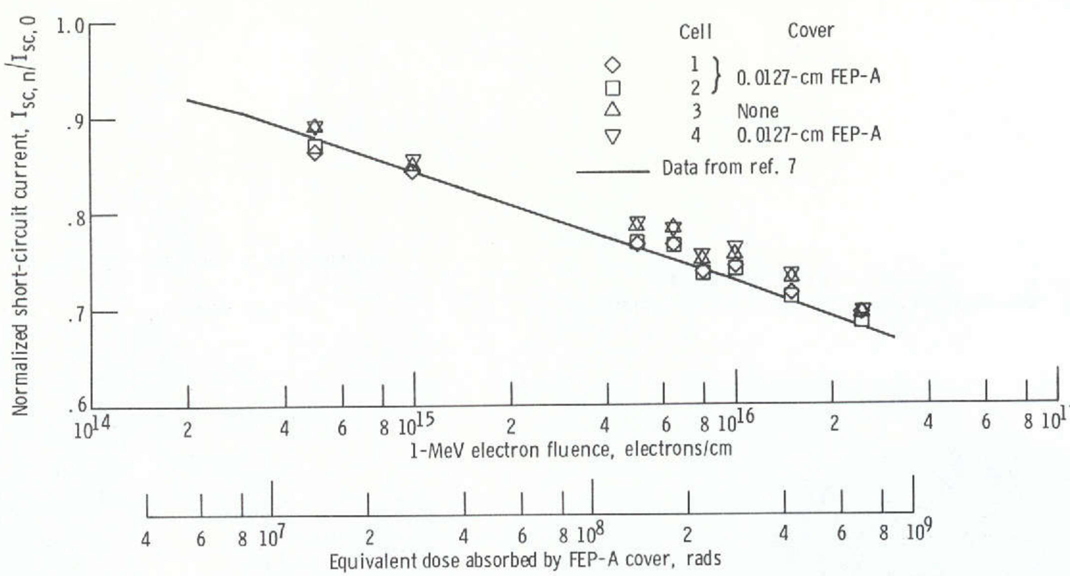

Figure 3. - Normalized short-circuit current as function of 1-MeV electron fluence. Total dose absorbed by FEP-A cover, 6.75×10^{8} rads.

Cell

4 3 2 1

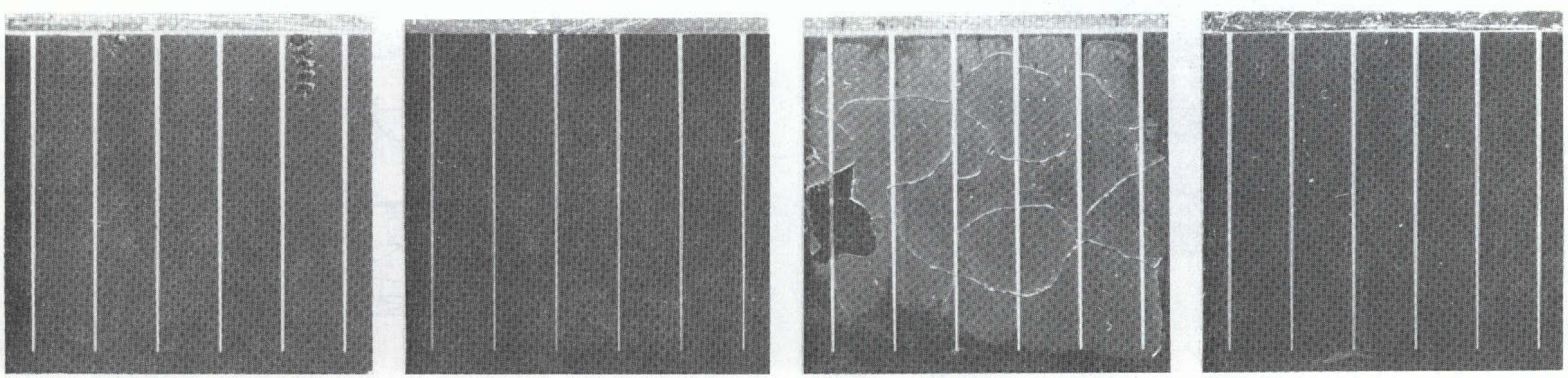

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Figure 4. - Cells irradiated at 2.5×10^{16} electrons per square centimeter after 14 days in open air. Cell 2 shows cracked FEP-A and delamination, and cell 4 shows effects of probing.

NASA-Langley, 1975

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